Color Homography: theory and applications (Supplementary Material)

Graham D. Finlayson[1,*], Han Gong[1,*], and Robert B. Fisher[2]

[1]School of Computing Sciences, University of East Anglia
[2]School of Informatics, University of Edinburgh
[*]denotes co-first authors.

September 24, 2017

Abstract

Image colors of the same scene are related by an homography when the capture conditions – illumination color, shading and device – change. In this supplementary material, we show the additional color homography results for illumination mapping, color correction, additional model tests, and color transfer approximation.

1 Illumination Mapping

Figure 1 shows three examples of illumination mapping by using color homography.

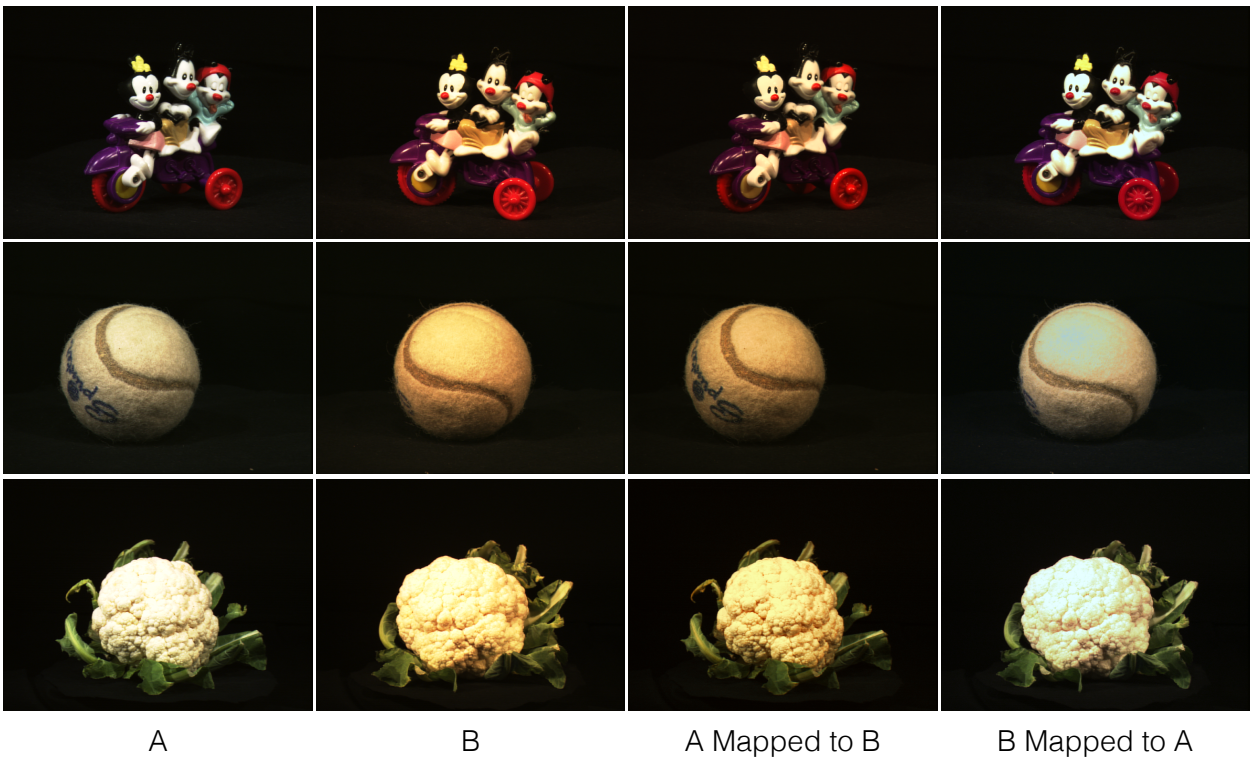


Figure 1: The first and second columns (i.e. image A and B) show images under two different lights. A homography is found that best maps the chromaticities in A to B and resulting in the outputs shown in the third column. When we map an image in B to A using a homography we obtain, its resulting image is shown in 4th column.

2 Color Correction

The individual color correction results and its RAW and sRGB images, corresponding to Table I of our paper, are shown here and in the following pages. The ΔE RGB error between two RGB vectors $\underline{p}$ and $\underline{q}$ is calculated as $||\underline{p}-\underline{q}||$. Typically, this is a small number and thus we show the error multiplied by 10^2. The compared methods are Least-Squares (LS), Root-Polynoimal (RP) [3], Alternating Least Squares (ALS) [4], and Homography.

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	4.87	5.25	10.22	11.43
RP	4.01	4.04	9.58	10.84
ALS	2.09	1.88	4.13	5.11
Homography	1.99	1.89	4.28	5.36

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	5.93	6.18	10.4	11.88
RP	4.74	4.82	11.02	11.73
ALS	2.33	2.18	4.59	5.05
Homography	2.23	1.88	4.87	5.5

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	5.66	5.75	12.28	15.72
RP	6.18	5.93	15.5	17.61
ALS	3.02	1.73	11.51	23.48
Homography	2.89	1.64	10.67	22.04

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	2.86	2.38	5.47	5.63
RP	2.66	2.45	5.9	5.93
ALS	2.28	2.05	4.78	5.2
Homography	2.17	1.84	5.01	5.5

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	3.19	2.72	5.74	6.07
RP	3.21	2.66	7.38	7.64
ALS	2.71	2.44	5.34	5.44
Homography	2.64	2.34	5.82	5.93

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	3.44	2.57	11.41	24.47
RP	4.18	3.79	9.55	9.55
ALS	3.05	2.18	10.16	20.26
Homography	2.78	1.84	8.32	14.8

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	3.36	2.28	7.49	8.12
RP	2.67	2.15	7.28	9.87
ALS	2.71	2.2	6.44	6.61
Homography	2.56	2.34	6.12	6.26

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	3.72	2.61	8.74	10.65
RP	3.1	2.36	8.88	11.73
ALS	3.16	2.6	7.54	9.14
Homography	3.05	2.87	7.53	7.56

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	4.15	2.68	15.76	21.4
RP	4.05	3.59	10.72	13.7
ALS	3.47	2.03	13.62	19.86
Homography	3.46	2.72	10.78	15.66

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	5.39	4.76	9.98	11.84
RP	3.23	2.66	6.85	7.62
ALS	3.71	3.72	6.48	8.18
Homography	3.44	3.06	6.91	7.24

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	5.86	5.49	10.09	10.96
RP	3.76	2.88	7.67	8.95
ALS	4.06	3.87	7.34	8.21
Homography	3.8	3.61	7.09	7.26

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	6.42	4.82	18.51	34.15
RP	4.83	3.86	9.98	10.23
ALS	5.57	4.58	15.57	22.32
Homography	5.14	4.19	13.69	19.43

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	7.93	7.15	16.79	20.59
RP	6.07	6.68	12.84	13.09
ALS	4.37	4.47	9.86	11.52
Homography	3.86	2.43	12.86	12.92

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	9.97	10.8	19.64	21.3
RP	7.22	7.76	14.53	15.57
ALS	4.73	4.79	11.57	11.93
Homography	4.28	2.85	12.98	13.4

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	8.8	7.86	21.31	27.66
RP	9.36	10.37	18.2	18.71
ALS	4.66	3.82	15.14	31.12
Homography	4.22	2.14	20.25	30.02

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	6.97	6.21	13.4	15.26
RP	8.16	8.03	15.21	15.97
ALS	4.04	3.66	10.07	11.21
Homography	3.49	2.03	12.87	12.94

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	6.73	6.47	12.44	13.28
RP	9.77	8.19	19.14	20.43
ALS	4.31	4.06	9.36	11.81
Homography	3.89	2.76	11.42	13.64

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	10.04	9.71	24.01	40.61
RP	13.12	12.71	26.41	31.95
ALS	4.36	3.32	14.64	30.56
Homography	3.8	1.74	19.75	30.3

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	10.32	9.6	18.09	20.7
RP	5.25	3.83	14.91	24.78
ALS	4.78	3.25	10.81	12.21
Homography	4.01	2.72	12.04	15.2

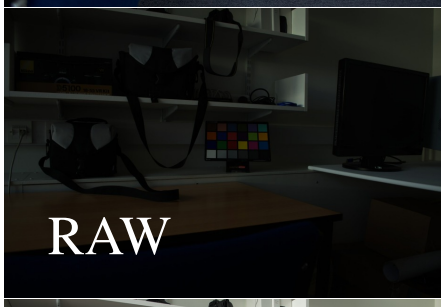
ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	11.87	11.03	22.6	25.1
RP	6.16	4.12	16.42	26.67
ALS	5.49	4.3	12.06	14.44
Homography	4.85	2.84	14.29	16.1

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	13.41	12.53	27.11	33.63
RP	8.27	5.89	24.92	38.87
ALS	4.72	3.21	14.23	27.75
Homography	4.09	2.53	15.19	28.47

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	7.01	6.85	12.6	13.74
RP	6.03	6.05	12.34	13.4
ALS	4.32	4.42	10.2	10.67
Homography	3.67	2.37	12.93	14.41

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	9.48	9.25	22.61	22.74
RP	7.28	7.74	15.79	15.85
ALS	4.67	4.53	9.39	11.7
Homography	4.09	2.86	12.66	13.16

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	7.8	7.48	14.67	17.66
RP	9.37	8.56	21.19	21.93
ALS	4.75	3.43	14.85	28.74
Homography	4.05	2.39	19.44	27.31



ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	6.58	6.28	12.94	15.21
RP	5.35	5.17	10.88	12.34
ALS	4.7	4.21	8.85	8.98
Homography	4.35	3.48	9.18	9.93

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	6.9	6.38	14.79	14.85
RP	6.22	6.51	12.82	13.95
ALS	5.13	4.12	9.93	10.41
Homography	4.82	3.93	10.62	10.93

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	7.75	6.53	19.63	35.24
RP	8.38	8.68	19.05	24.69
ALS	5.6	4.78	13.55	23.32
Homography	5.22	4.91	12.62	21.12

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	4.99	4.13	10.42	10.7
RP	3.83	1.61	12.46	14.26
ALS	3.27	2.74	7.71	8.06
Homography	3.14	2.58	8	8.89

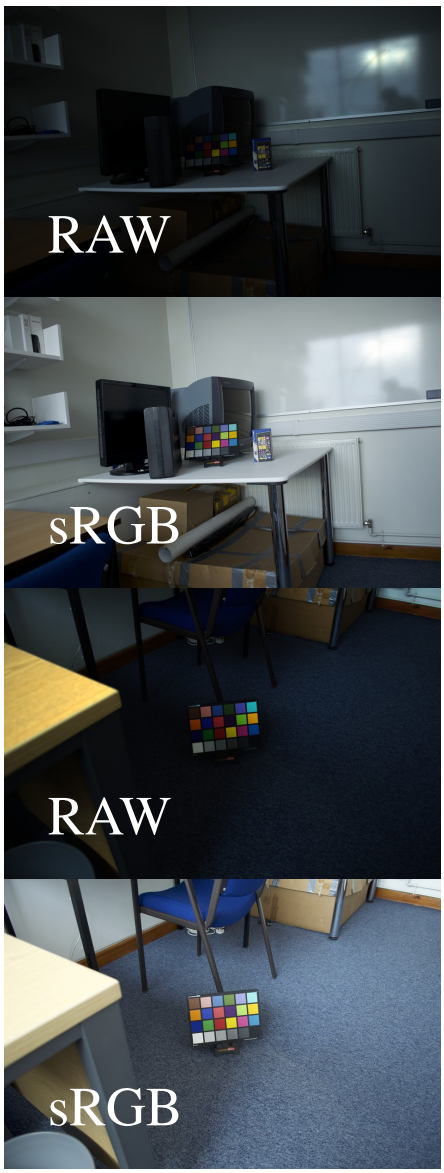
ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	5.52	4.64	11.79	11.96
RP	4.36	1.93	13.82	15.41
ALS	3.63	3.03	8.53	8.86
Homography	3.5	2.74	9.09	9.39

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	7.01	5.73	17.73	31.8
RP	6.17	2.27	22.06	23.36
ALS	4.31	2.92	14.99	27.14
Homography	4.36	2.84	14.58	26.89

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	4.6	4.33	9.36	9.49
RP	3.61	1.84	10.49	12.02
ALS	3.71	3.42	7.83	9.13
Homography	3.45	2.93	8.14	9.87

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	5.12	4.74	10.35	11.01
RP	4.21	2.67	11.62	13.16
ALS	4.35	3.99	9.54	10.44
Homography	4.12	3.98	10.6	11.84

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	5.63	3.88	15.84	31.32
RP	6.1	2.74	17.86	21.74
ALS	4.41	2.96	14.41	23.16
Homography	4.13	3.73	12.07	14.57



ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	7.39	7.32	15.33	18.84
RP	13.24	7.79	47.99	53.92
ALS	3.87	3.32	9.69	10
Homography	3.61	2.92	9.1	10.61

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	8.28	8.14	18.55	21.28
RP	15.77	9.25	56.28	61.81
ALS	4.42	3.77	9.88	10.02
Homography	4.15	3.04	9.96	11.06

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	7.78	5.84	21.93	41.69
RP	21.92	12	80.46	111.78
ALS	4.19	2.8	13.15	29.38
Homography	4.01	3.1	13.76	29.83

ΔE Lab	Mean	Median	95% Quant.	Maximum
LS	7.77	7.21	17.41	18.24
RP	9.63	8.38	23.01	26.5
ALS	4.46	3.19	10.33	10.34
Homography	3.62	2.88	9.06	10.47

ΔE Luv	Mean	Median	95% Quant.	Maximum
LS	8.66	7.77	17.27	21.11
RP	11.24	10.08	24	26.5
ALS	5.24	4.39	11.02	11.16
Homography	4.16	2.78	10.21	10.89

ΔE RGB	Mean	Median	95% Quant.	Maximum
LS	10.49	7.08	27.73	36.09
RP	15.96	13.33	45.49	53.71
ALS	4.56	3.27	16.26	31.56
Homography	4.03	3.02	14.02	29.88

Figure 2: Comparison for color transfer approximation by a 3×3 homography matrix and a diagonal matrix chromaticity change match (scores shown at the top).

Figure 3: Approximating color change in the scene with shadows.

3 Additional Tests for Color Homography Model

We carry out two additional tests for color homography model:

3.1 Test of the efficacy of A Diagonal Chromaticity Change Model

Previous literature suggests that a 3×3 diagonal matrix is sufficient for modeling illumination change [2, 1]. Here we test how well a diagonal matrix works for color transfer. Figure 2 contrasts the homography output with that of the diagonal version. Clearly, diagonal model works less well. The diagonal chromaticity change model is written as:

$$DID' \approx O \tag{1}$$

where D' is a 3×3 diagonal matrix. As before D encapsulates per-pixel shading factors, we find D and D' using the ALS minimization.

3.2 Approximating Color Change in Scenes with Shadows

Shadow and non-shadow areas are lit by different illuminants rather than a single global illuminant. Therefore, we are also interested in whether a global homography can empirically approximate the color transfer of a shadow scene lit by at least two illuminants. In Figure 3, the color transfer result of a shadow scene is approximated by a color homography. The approximation result is visually close to the original color transfer which is also verified by good quantitative metrics.

4 Color Transfer Approximation

Tables 1,2 and 3 show the complete per-method errors corresponding to Table IV in the main paper. An image in each row is color transferred by 4 different color transfer methods. And, these color transfer results are approximated by 2 color transfer approximation methods (i.e. 3D similarity [6] and our shading homography).

	3D Similarity [6]				Homography			
Method	[5]	[7]	[8]	[9]	[5]	[7]	[8]	[9]
Image 1	27.80	27.42	29.83	25.42	31.56	31.62	36.97	30.87
Image 2	25.37	24.14	24.78	31.97	32.68	30.03	34.59	34.93
Image 3	23.22	21.74	22.64	30.45	36.43	30.26	35.29	33.58
Image 4	27.11	26.68	25.12	30.07	40.99	36.05	37.88	43.43
Image 5	31.68	30.49	31.54	26.10	28.97	29.51	35.00	35.37
Image 6	26.25	26.73	28.73	28.36	28.41	29.30	36.76	31.95
Image 7	26.54	25.05	25.76	27.09	39.34	36.59	44.49	44.03

Table 1: PSNR error between the original color transfer result and its approximation.

	3D Similarity [6]				Homography			
Method	[5]	[7]	[8]	[9]	[5]	[7]	[8]	[9]
Image 1	0.93	0.91	0.88	0.89	0.96	0.97	0.98	0.98
Image 2	0.97	0.94	0.93	0.98	0.96	0.94	0.98	0.98
Image 3	0.93	0.86	0.72	0.96	0.97	0.92	0.97	0.98
Image 4	0.88	0.87	0.81	0.89	0.99	0.98	0.99	1.00
Image 5	0.97	0.84	0.92	0.91	0.92	0.88	0.95	0.96
Image 6	0.93	0.78	0.85	0.89	0.83	0.78	0.97	0.96
Image 7	0.75	0.72	0.78	0.67	0.97	0.93	0.99	0.99

Table 2: SSIM error between the original color transfer result and its approximation.

	3D Similarity [6]				Homography			
Method	[5]	[7]	[8]	[9]	[5]	[7]	[8]	[9]
Image 1	0.95	0.87	0.82	0.88	0.84	0.81	0.83	0.92
Image 2	0.93	0.74	0.83	0.92	0.88	0.83	0.82	0.91
Image 3	0.82	0.71	0.63	0.91	0.76	0.69	0.62	0.97
Image 4	0.85	0.73	0.75	0.79	0.72	0.62	0.64	0.92
Image 5	0.87	0.82	0.86	0.88	0.86	0.85	0.83	0.90
Image 6	0.86	0.68	0.53	0.61	0.74	0.58	0.77	0.74
Image 7	0.78	0.72	0.81	0.66	0.64	0.63	0.79	0.77

Table 3: HI error between the original color transfer result and its approximation.

Figure 4,5,6,7 contain the color transfer approximation results based on 7 classic source and target image pairs and four popular color transfer methods [5, 7, 8, 9]. These visual results correspond to the quantitative evaluation results shown in Tables 1,2 and 3.

Figure 4: Visual comparisons. Original color transfer results of [5] and its approximations. Compared with Column 3 (3D similarity), Images of Column 4 (shading homography) are generally the closer approximations to the "original color transfer" outputs (Column 2).

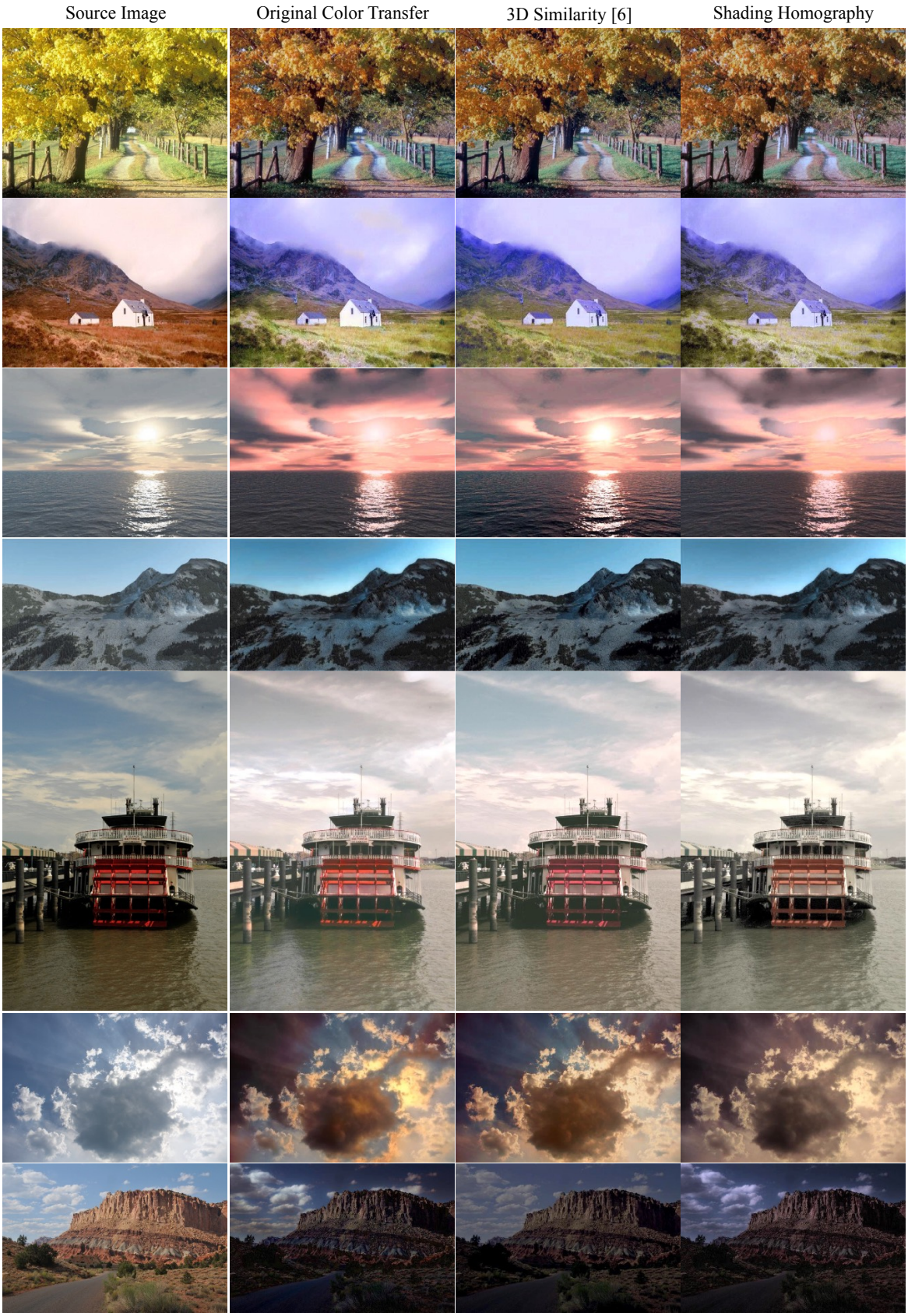


Figure 5: Visual comparisons. Original color transfer results of [7] and its approximations. Compared with Column 3 (3D similarity), Images of Column 4 (shading homography) are generally the closer approximations to the "original color transfer" outputs (Column 2).

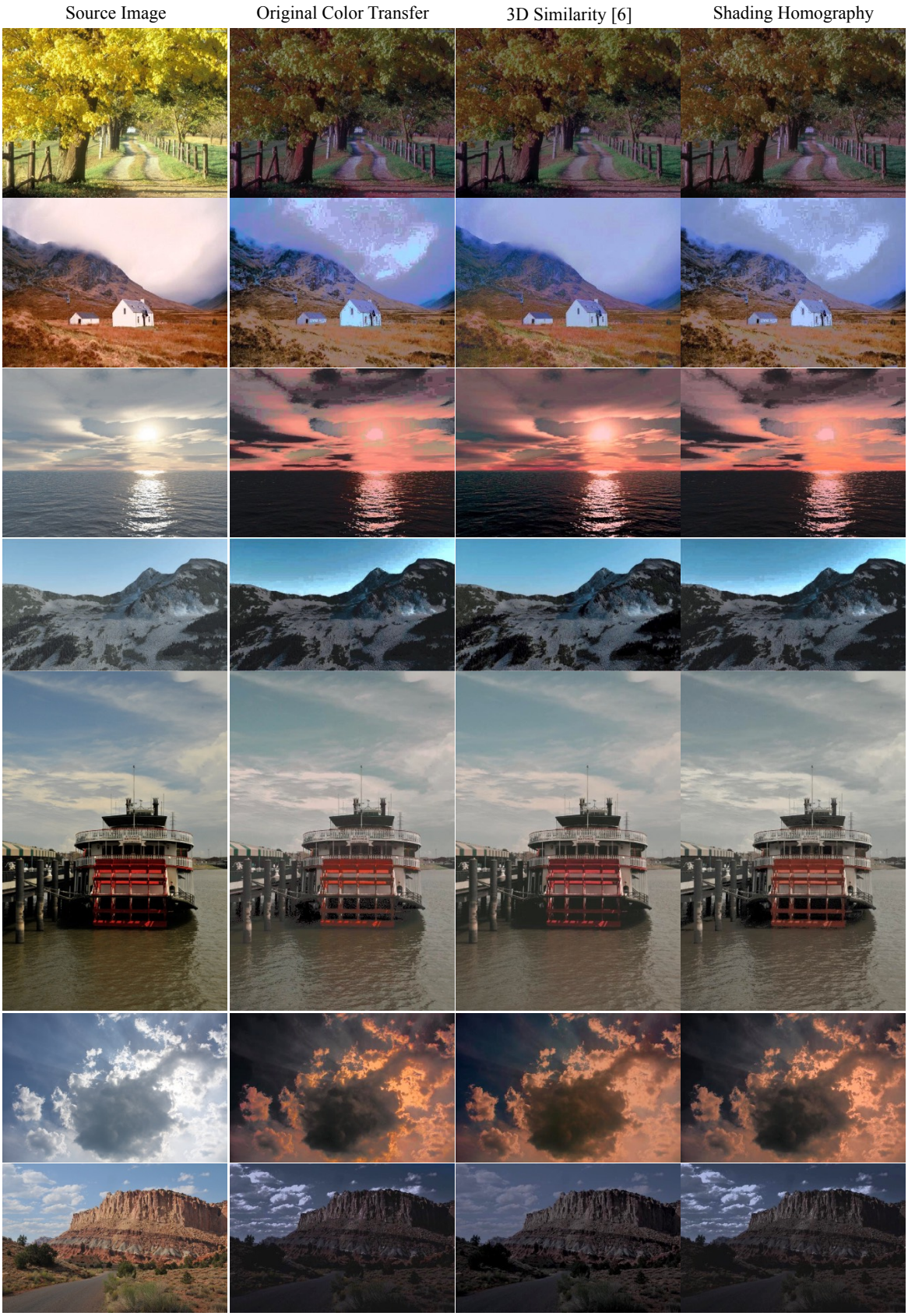


Figure 6: Visual comparisons. Original color transfer results of [8] and its approximations. Compared with Column 3 (3D similarity), Images of Column 4 (shading homography) are generally the closer approximations to the "original color transfer" outputs (Column 2).

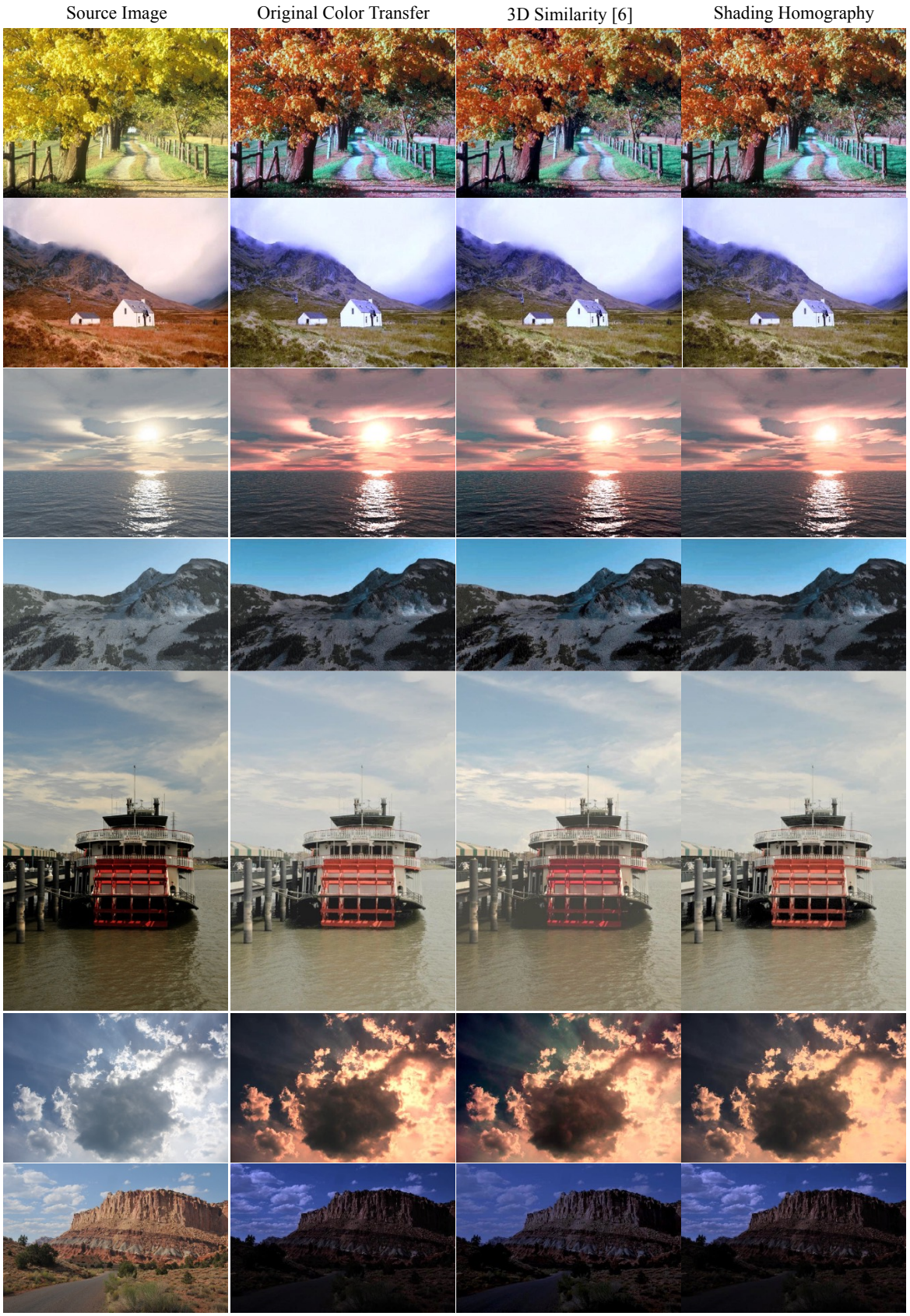


Figure 7: Visual comparisons. Original color transfer results of [9] and its approximations. Compared with Column 3 (3D similarity), Images of Column 4 (shading homography) are generally the closer approximations to the "original color transfer" outputs (Column 2).

References

[1] H. Y. Chong, S. J. Gortler, and T. Zickler. The von kries hypothesis and a basis for color constancy. In *International Conference on Computer Vision*, pages 1–8, 2007. 7

[2] G. Finlayson, M. Drew, and B. Funt. Spectral sharpening: sensor transformations for improved color constancy. *Journal of the Optical Society of America A*, 11(5):1553–1563, May 1994. 7

[3] G. D. Finlayson, M. Mackiewicz, and A. Hurlbert. Color correction using root-polynomial regression. *Transactions on Image Processing*, 24(5):1460–1470, 2015. 2

[4] G. D. Finlayson, M. Mohammadzadeh Darrodi, and M. Mackiewicz. The alternating least squares technique for non-uniform intensity color correction. *Color Research & Application*, 40(3):232–242, 2015. 2

[5] R. M. H. Nguyen, S. J. Kim, and M. S. Brown. Illuminant aware gamut-based color transfer. *Computer Graphics Forum*, 33(7):319–328, Oct. 2014. 8, 9, 10

[6] F. Pitié and A. Kokaram. The linear monge-kantorovitch linear colour mapping for example-based colour transfer. In *European Conference on Visual Media Production*. IET, 2007. 8

[7] F. Pitié, A. C. Kokaram, and R. Dahyot. Automated colour grading using colour distribution transfer. *Computer Vision And Image Understanding*, 107(1-2):123–137, July 2007. 8, 9, 11

[8] T. Pouli and E. Reinhard. Progressive histogram reshaping for creative color transfer and tone reproduction. In *International Symposium on Non-Photorealistic Animation and Rendering*, pages 81–90, New York, NY, USA, 2010. ACM. 8, 9, 12

[9] E. Reinhard, M. Ashikhmin, B. Gooch, and P. Shirley. Color transfer between images. *IEEE Computer Graphics And Applications*, 21(5):34–41, Sept. 2001. 8, 9, 13